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SIZING AND COST ANALYSIS OF SOLAR PV PANEL ARRAYS FOR AN OFF-GRID DC - AIR CONDITIONER FOR A TESTING FACILITY AT MANGOSUTHU UNIVERSITY OF TECHNOLOGY (SOUTH AFRICA)

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ABSTRACT

In this journal paper, the sizing, selection, and cost analysis of a 100-percent off-grid DC-powered air conditioning (AC) system were investigated. The AC system was combined with a photovoltaic (PV) system which incorporated solar PV panels (modules), a charge controller, a DC/AC converter (solar inverter), and deep cycle batteries. Now solar power is essential to operate or power the AC system and it can be utilized in regions where there is zero electricity.The first step in the investigation involved estimating the load due to cooling for the designated area and this was established to bealmost 1-ton refrigeration (1.0 TR)or, in other words, a 3.52 kW cooling capacity unit would suffice this requirement.According to past studies, a package-type vapor compression system suffices this requirement. The estimation of the cooling load and the design comfort conditions required for the selected area to be cooled was all based on the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standards. The cooling load items such as lighting heat gain, occupancy heat gain, infiltration and ventilation heat gain, etc. were all incorporated in the analysis. To power this unit, 6x 335 watts solar panels were required in series connection. The performance coefficient (CoP) of the air conditioning system was computed and found to be 2.7, (this falls in the normal range of 2- 4). The results of the analysis show that 2 x 48 V DC, 150 Ah batteries were required to provide backup power for the system for 8-hour operation, or 6 x48 V DC, 150 Ah batteries for 24-hour operation. The cost analysis showed that the final system was estimated to be approximately R96500 or $ 6829 (USD)to provide for 24-hour operation and 100 % off-grid connection.

***KEYWORDS:** renewable energy, solar-powered air conditioning, sizing, cost analysis, AC, DC, photovoltaic, cooling load estimation, ASHRAE standards, CoP, 1-ton refrigeration.*

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Original Article

1.0 INTRODUCTION

Solar energy is a renewable energy source derived from planet earth's natural resources and it can be considered infinite, inexhaustible and this is the reason why it is continually attracting huge interest worldwide. A solar energy system can be categorized into two main streams, the thermal energy stream (i.e. conversion of solar energy into thermal energy) and the photovoltaic (PV) stream (i.e. conversion of solar energy into electrical energy). It must be realized, however, that not all the solar radiation falling from the sun onto the photovoltaic cells is converted into useful electricity, as some are reflected or deflected and this consequently leads to a decrease in electricity conversion efficiency.

Global warming, reduction of the ozone layer, and the ever-increasing fossil fuel costs during the last two decades have led scientists to design and control building energy systems. Since solar energy is always in abundance, easily available on the earth's surface, and a source of renewable energy (i.e. clean energy), it's more sensible

to replace conventional energy with solar energy. The main drivers behind solar energy are to reduce carbon dioxide (CO_2) gas emissions and other toxic gases that contribute to global warming and ozone layer reduction.It is for this reason that solar energy has gained so much attention and thus plays a pivotal role in building energy systems.

Nowadays, if comfortable and desirable conditions are requisite in every building or office space, then air conditioning systems are no longer a luxury item, but an essentiality. In current years, research on solar-powered air conditioning has improved to a considerable extent. The solar industry is fairly novel in South Africa, hence it is crucial to know South Africa's sunshine when compared to other parts of the world and the potentiality this has for PV technologies(refer to the world in solation map shown in Figure 1).

"In South Africa, the mean sunshine hours per annum for most regions is larger than 2 500 hours, with a mean solar-radiation level falling between 4.5 kWh/m^{2}and 6.5kWh/m^{2}per day." [2]. Hence, this is an opportune chance for the South African market to take advantage of when compared to the solar revolution in the world market. The climatic conditions for South Africa can be considered relatively dry with a mean annual rainfall of 465 mm when contrasted with a mean of 805mm for the world. Now, water is not required for the operation of solar PV cells, hence the less rainfall, the greater the chances of sunshine. This results in a larger quantity of energy been generated from the solar PV cells, which epitomizes yet another huge advantage that South Africa has due to its natural solar resources. The above factors make a significant contribution to the vast development opportunities in South Africa's solar market industry.

Solar radiation is at its peak during the summer seasons when cooling is the most, hence this makes air conditioning an enticing field for solar energy applications. This research paper looks at the need for new evolving, state-of-the-art air conditioning technologies, which have low operational costs and minimal environmental impacts, and this is what is in great demand today.

As mentioned earlier, a solar PV system is a clean, renewable energy system that utilizes PV panels(modules) to convert the sun's rays into useful or quantifiable electricity. The PV-generated electricity can either be stored using deep cycle batteries, directly used, or fed back into the grid network. Solar PV systems are clean and dependable energy sources that can be suited for a host of applications viz. residential, industry, farming, livestock, etc. [3].

Numerous studies were carried out in an attempt to develop more effective solar-powered AC systems. Okumiya et al.[4]performed studies of a solar-thermal AC system for office buildings. Zhai et al.[5]completed the design and installation of a solar-powered adsorption AC system. Nakahara et al.[6]studied the role of compound parabolic collectors in AC systems. Li and Sumathy[7]studied the performance of a solar absorption AC system and concluded that the temperature (generator) entering the chilling unit was the most significant design parameter in the manufacture of solar-powered AC systems. Al Qdah[8] investigated the design and performance characteristics for PV- powered AC systems. Rachid et al.[9]optimized the PV system and computed the amount of the sun's radiation striking on it.

The main objective of this investigation is to cool a designated building space using the PV system. The solar energy generated from the panels, which are mounted on the rooftop of the building will be utilized to power the DC motor which will, in turn, run the vapor compression system while the complete system will be 100% off-grid.

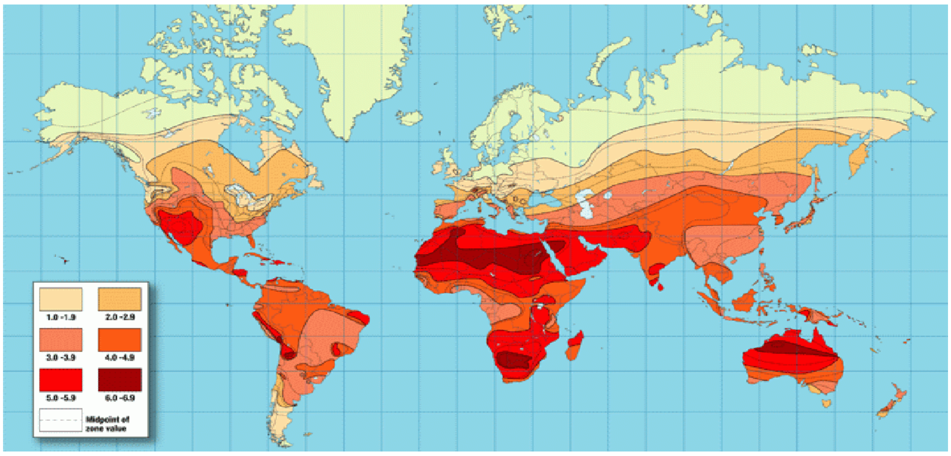

Figure 1: World Isolation Map That Reveals South Africa's Solar Potential [1]

2.0 MATERIALS AND METHODS

For the analysis, the space to be cooled is the test facility with the dimensions 4.5 mx 3.6m x 2.5 msituatedon the rooftop of Mangosuthu University of Technology (MUT)in Durban, South Africa. The main objective isto cool the designated space for 8 hours. The cooling load estimation was based on building/site construction, outside and inside temperatures, and relative humidity. For Durban's climatic conditions, a maximum design temperature of 34 ºC was used for the outside. The comfort conditions inside the room were taken as 25 ºC(standard room temperature) with a relative humidity of 50%.

2.1 Specifications of Air Conditioning Equipment

The designated specifications of the air conditioning unit are outlined in Table 1 and the detailed cooling load calculations, based on the latent and sensible heat loads, can be found in Table 3.

Table 1: Air conditioner Unit Specifications

Type of System	12 000 BTU (split-type AC unit)
Unit capacity	1.0 TR (3.52 kW)
Maximum Input Power	2.0 kW
Input Voltage	220 V to 240 V~50 Hz frequency
Rated Cooling Input	1.32 kW

The sizing up of a PV system with battery backup requires the use of tools or instruments which are readily available on the market. The steps detailed below give a summary of the materials and methods used for the experimentation.

2.2 Compilation of Essential Meteorological and Atmospheric Data

The design temperatures, relative humidity, day-to-day and yearly solar radiation values for the selected site are referred to as meteorological data used for the 8-hours operational period. Now Durban has been particularly noted for summers that are warm, overbearing, and humid. The winters are long but comfortable, and it is windy with mostly clear skies throughout the year. Typically, the temperature ranges from 14ºC to 31ºC and it rarely drops below 14 ºC or above 31 ºC. On average, there are 2345 hours of sunshine available per year and 6.5 hours of sunshine per day [10].

Table 2: Outdoor Design Conditions – Durban

GPS location	29º57'S, 30º56'E
design dry-bulb temperature (outdoor)	35°C
design wet-bulb temperature (indoor)	30°C
design dry-bulb (indoor)	25°C
Relative humidity	50% RH
Mean wind velocity	2.5 $m.s^{-1}$
Mean solar irradiation	4.5 kWh/m^2 to 6.5 $kWh/m^2/day$

2.3 Site Assessment

For this analysis, the site chosen as the required cooling space is the testing facility called the STAR lab (Solar Thermal Applications and Research Laboratory)situated at the rooftop of MUT with GPS coordinates: latitude 29°57'S and longitude 30°56'E and at aheight of 14 m above the mean sea level. The cooling space dimensions as given before are 4.5 m x 3.6 m x 2.5 m with a floor area of 16.2 m^2 and this is illustrated in the photograph (see Figure 2).

Figure 2: STAR Labtesting Facility

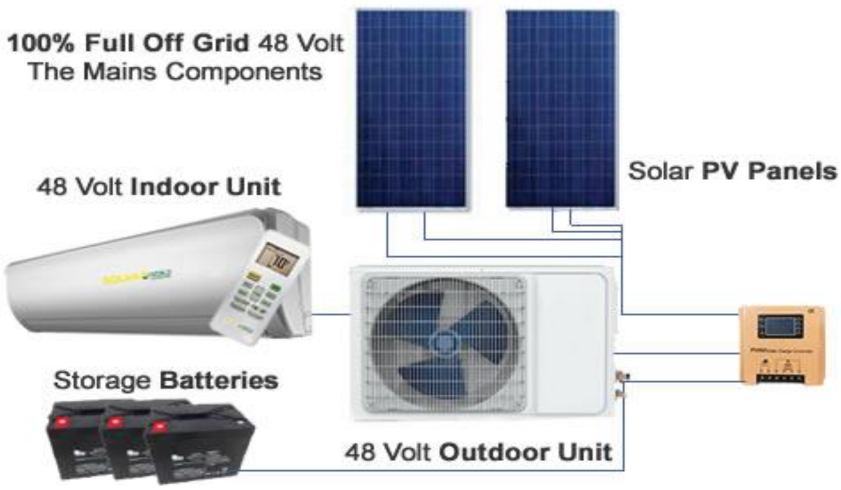

Figure 3: The Main Components of the 48 V DC, 100 % off-Grid AC System

2.4 Cooling Load Requirement

The objective is to cool the specified space for 8 hours. For summer, 34 ºC was used as the maximum design temperature and 25 ºC was used for the comfort conditions inside the room with a relative humidity of 50%. The quantity of heat energy that is extracted from the test site to maintain a constant inside air temperature is referred to as the cooling load. The cooling load temperature difference method (CLTD) was adopted to find the cooling load of the test site. This is a standard method of determining the cooling loads of test sites and has been adopted by ASHRAE standards.[10]. The outside cooling load is comprised of sensible heat loads through the roof, walls, and floor and heat conduction through window glass; solar heat load through window glass and cooling load through partitions; ceilings and floors. The inside cooling load is comprised of occupant's heat gain;indoor lights and office equipment; appliances, infiltration of outside air, and ventilation of inside air. The total load is the sum of the inside and outside loads or both sensible and latent loads. By adhering to the procedures outlined for determining space design cooling loads as per the CLTD method and adding a factor of safety of 15%, it was found that a 1.0 TR was required as the final cooling load for the test site shown in Figure 2.

2.5 Alternative Method to Verify Cooling Load Requirement

According to a Singapore Government Agency website [11], a useful rule of thumb for calculation of the cooling load requirement is to divide the area of the space to be air-conditioned by 5, i.e.:

Cooling Capacity required in kW

$$=\frac{Total\ area\ to\ be\ air\ conditioned}{5} = \frac{16.2\ \mathrm{m}\hat{}2}{5} = 3.25\ \mathrm{m}\hat{}2$$

Now, to convert to Btu.hr^{-1}, multiplying the kW result by 3412 (since 1 kW = 3 412 Btu.hr^{-1})this gives 3.25 x 3412= 11090 Btu, which almost fits a 12000 Btu unit or 1.0 TR unit.

2.6 Sizing up the Air Conditioning System

The air conditioning equipment was selected on the basis of the cooling load calculations and with the specifications: (1.0TR) split-unit, 220-V, rated cooling input power 1.32kW, which provides an acceptable CoP of 2.7. If the energy produced by a system is divided by the energy that is input into the system, then this ratio is referred to as the CoP. As a rule of thumb, the higher the CoP, the more efficient the compressor, and the lower the operational cost. The CoP is highly dependable on operational conditions, especially kelvin and relative temperatures between a heat sink and system and ranges from 2 to 4.

2.7 PV System Sizing and Material Selection

The solar-powered PV system specifications were selected based on the capacity of the air conditioning unit and climatic conditions i.e. intensity of solar radiation ~ 6.5 kWh/m^2/day.

A PV system is a set of components created to provide working electric power for a host of applications [12]. The energy from the sun is transferred to our planet in two main forms, light and heat. Now solar-powered systems are categorized into two main types, as previously mentioned, solar thermal that converts heat to electricity, and solar PV that converts sunlight directly into workable DC electricity. An inverter is simply a device that converts DC power into AC power. The PV cells are made from wafers of semi-conducting material, the most popular in the solar market is silicon. The solar panels used in this experimentation are the Canadian solar panels of 335W capacity each. They are super high-

power poly PERC HiKU panels made from poly wafers and cell technologies and have a very high-level efficiency of 18%. When the sun's rays strike on a PV cell, an electric field is produced across the layers. The greater the intensity of the sun's rays, the greater the electric current produced and vice-versa. A panel or module is a group of cells mounted together so that it can be installed on the rooftop of houses, buildings, etc. To determine the number of PV panels that need to be installed, it is necessary to first determine the number of peak sun hours for the testing site in question.

Before moving ahead, it is necessary to also determine the power assumed to be generated from the PV modules based on the solar irradiation values of the test site.

The current and voltage that are transferred from the solar panels into the battery are adjusted via a charge controller. A very critical component in any PV solar array system is the battery which acts as an energy bank for the renewable energy system. The battery is essentially a storage device in which electricity generated is stored during cloudy days or at night when sunlight is not available. To apply this system in AC load, the inverter converts the DC electricity from the PV panels into AC load, which is a common type of load found in many households and it is relatively inexpensive.

Since the charge controller is responsible for regulating or controlling current from the PV modules it, therefore, has to stop the batteries from overcharging which could cause battery damage. So the charge controller essentially detects when the batteries are charged up to full capacity and then either break or reduce, the quantity of current passing to the batteries[13]. The solar energy obtained from the PV modules is converted into electrical energy and regulated by the charge controller either by supplying it directly to the load or charging the batteries. As the electricity generated from the PV module is in DC mode, an inverter is required to convert DC to AC since the compressor unit operates using AC mode. The electricity produced by the panel array and battery is DC at a steady or constant voltage. This voltage might not be similar to that which is required by the load, hence an inverter is required to convert DC to AC.

A voltage regulator is designed so that it automatically maintains a constant level of voltage. Referring to Table 1, it can be seen that the output cooling power for a 12000 BTU unit is 3.52 kW and the rated cooling input power consumption is 1.32 kW, hence the CoP is equal to 2.7

$$CoP_{cooling} = \frac{Desired\ Output\ Power}{InputPower} = \frac{3520\ W}{1320\ W} = 2.7[14]$$

Hence 1320 W is required with 8 working hours per day

Input power x working hours in a day = work hours per day

1320 x 8 = 10560 W.h/day

Minimum hours of sunlight is 6 hours/day, hence

$$Total\ load\ capacity = \frac{work\ per\ day}{minimum\ hour\ of\ sunlight\ per\ day} = \frac{10{,}560\ W.h/day}{6\ h/day} = 1760\ W$$

Therefore a PV system with a capacity of 1760 W is required.

Canadian Solar KuMax 335W panels were selected as materials for this investigation using polycrystalline solar cells with an efficiency of 18 %.The number of panels required is

$$Number\ of\ panels = \frac{Total\ Load\ Capacity}{Power\ Output\ for\ 1\ panel} = \frac{1760}{335} = 5.3\ or\ 6\ panels$$

Thus 6x 335 W solar panels are required, assuming a voltage drop of 30% for 150 Ah batteries

$$150\ x\ 30\% = 45\ Ah$$

Now DC air conditioners require 48 V batteries to function, hence the most economical option will beto use 8x 6 V golf cart batteries. Firefly carbon AGM 48 V batteries were selected. The minimum efficiency of a 48 V DC battery is 90%.

The actual amperes of the battery:$(\ 90\%\ x\ 150) - 45 = 90\ Ah$

The actual capacity of one battery: $90\ A.h, working\ hours : 8\ h$

The actual Amperage is $\frac{90\ Ah}{8\ h} = 11.25\ A$

The running current (no-load during start-up) of the air conditioning unit is $\frac{1320}{220} = 6\ A$ and the start-up current is22.8 A.

$Hence, number\ of\ carbon\ AGM\ batteries = \frac{22.8}{11.25} = 2\ ; for\ 8\ hour\ operation$

$and\ the\ number\ of\ carbon\ batteries\ for\ 1\ day = 2\ x \frac{24h}{8h} = 6\ ; for\ 24\ hour\ operation$

Finally, with total power stored: 1760 W, 6 x 48V, 150 Ah batteries

The inverter specifications are input 48 V, DC and output 220V~240 V, output power 5 kW, and the charge controllers 12 V each with charge rating 24 A with overload and short-circuit protection.

The total costs including installation of the final system is a figure ofR96 500 ($ 6850)as indicated in Table 4.

Table 3: Cooling Load Estimation [10]

	HEAT LOAD SOURCES	**LOAD (W)**
	walls, roof, and floor	1241
	window glasses	658
Sensible Heat Loads	occupancy of persons	75
	fluorescent lighting	281
	electrical appliances	200
	ventilation/infiltration of air	227
	Total Sensible Heat Gain→	∑2682 W
	occupancy of persons	150
	ventilation/infiltration of air	282
Latent Heat Loads	Total Latent Heat Gain→	∑432 W
	Total Heat Gain **Grand Total Heat Gain with15 % Safety Factor**	**∑3114 W** **∑3581 W** **(~ 1.0 TR)**

Table 4: Total Cost breakdown for Final System

Item No.	Item Description	Unit Price	Quantity	Net Price (ZAR)
1	Solaire 48 V DC, 12000 BTU AC unit	24,500	1	24,500
2	PERC HiKUsolar panels 335 W	1,835	6	11,010
3	DC Power controller 8 x15 A	8,000	1	8,000
4	Solar charge controller 40 amp	3,300	1	3,300
5	48 V DC Carbon AGMbatteries	3,675	6	22,050
6	Solar panel installation	3,600	1	3,600
7	Solar panel mounting brackets	4,900	1	4,900
8	Solar AC installation	3,600	1	3,600
9	Sundries and material	2,995	1	2,995
	Total Net Price VAT @ 15%			∑83,955 12,593
	TOTAL COSTS			**R96,548 (USD6850)**

3.0 RESULTS

For the cooling space, a cooling effect of 1.0 TR was estimated. As per market research, a package-type air-conditioning system would suffice in attaining the required cooling effect capacity. To satisfy this power requirement, 6 solar panels of 335 W_p each and 2 x 48 V DC Carbon AGM batteries with 150 Ah for every 8-hour operation are required. A schematic arrangement of the panels and the cooling unit is shown in Figure 4. The specifications for the inverter are input DC 48 V, output AC, 220 V - 240 V, output power 5 kW, and charge controller 12 V each with charge rating 24 A with overload and short-circuit protection.

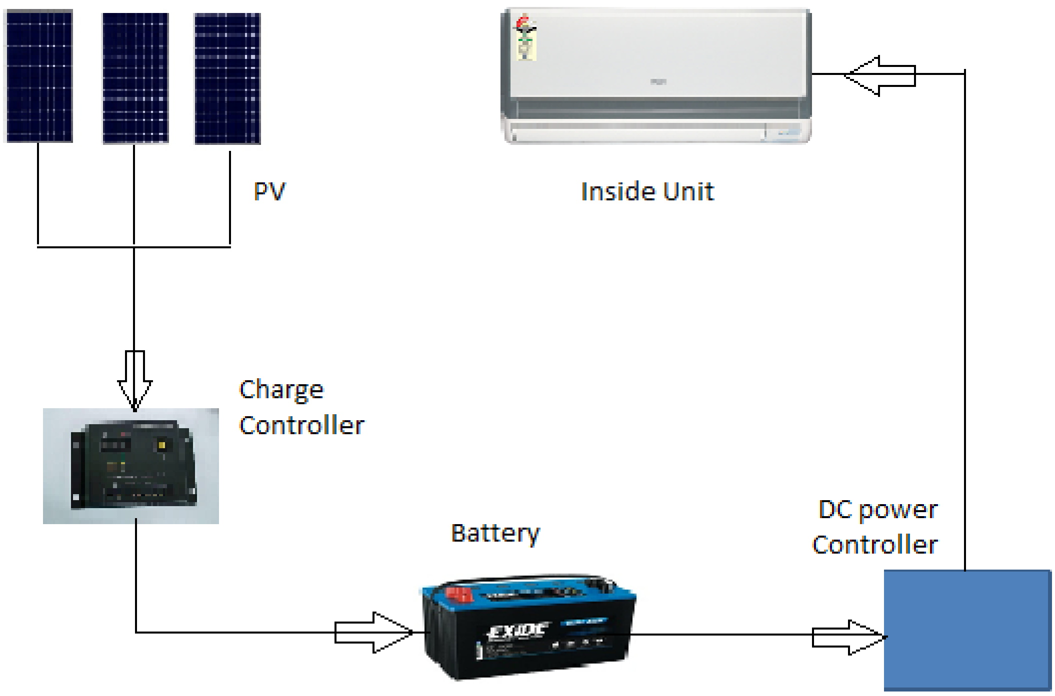

Figure 4: Final System Cycle [3]

4.0 CONCLUSIONS

Nowadays it has become eminent that one of the biggest problems facing human society is energy. By slowly shifting our focus to solar energy, we will not only save our environment from greenhouse gas emissions but also keep our environment clean and green for generations to come. The work described in this article is primarily focused on the design and size-up of a package-type air conditioning system that utilizes solar energy integrated with photovoltaics. The cooling capacity or cooling load for the selected space was first calculated at the outset to give a guesstimate of how to design and build the system with adequate electricity supplied to it. Results reveal that a 1.0TR (1 tonne) capacity unit was more than adequate and from past literature, the package-type vapor compression system suffices this requirement. In this particular case, 6 x 335 W_p panels,2 x 48 V DC, 150 Ah batteries are required to provide backup power for the system for 8-hours operation and 6x48VDC, 150 AhAGM batteries are required for a full 24-hours operation. The total cost including installation is R96,500 ($ 6850), which is high but this can be recouped in 4 to 6 years. Finally, this article represents is a typical scenario that addresses climatic changes and offers a solution to reduce or save input energy losses by utilizing DC-powered compression systems for a cleaner environment.

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